AD NUMBER

AD819272

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; JUN 1967. Other requests shall be referred to Naval Electronics Systems Command, Code 05143, Washington, DC 20360.

AUTHORITY

nesc ltr, 11 aug 1971

AD819272

Report No. 03-67-53

THIRD INTERIM ENGINEERING REPORT

for

DEVELOPMENT AND FABRICATION OF SOLID-STATE HIGH-SPEED OPTICAL DETECTORS

This Report Covers the Period

16 February 1967 to 15 May 1967

Texas Instruments Incorporated
13500 North Central Expressway
Dallas, Texas 75222

Navy Department
Bureau of Ships
Electronics Division

Contract No. NObsr 95337
Project No. SF021-02-01
Task No. 9349

June 1967

Report No. 03-67-53

THIRD INTERIM ENGINEERING REPORT

for

DEVELOPMENT AND FABRICATION OF SOLID-STATE HIGH-SPEED OPTICAL DETECTORS

This Report Covers the Period

16 February 1967 to 15 May 1967

Texas Instruments Incorporated
13500 North Central Expressway
Dallas, Texas 75222

Navy Department
Bureau of Ships
Electronics Division

Contract No. NObsr 95337
Project No. SF021-02-01
Task No. 9349

June 1967

STATEMENT #2 UNCLASSIFIED

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of NAVAL ELECTRONICS SYSTEMS CMD
ATTN: "CODE 05143"
WASH. D.C. 20360

ABSTRACT

Work continued on development and fabrication of a high-speed silicon avalanche photodetector optimized for operation at 0.9 μm. During this quarter work was concentrated on the fabrication and characterization of diodes.

A run of NPπP diodes was completed with avalanche breakdown taking place in the active region instead of the edge. However, there were microplasmas, and the gains were low.

A new run of the graded-guardring structure was completed, and the yield was high. With this run and the run processed earlier there are sufficient diodes to meet the contract requirements.

Twenty state-of-the-art samples were characterized and delivered. Results on the N^+P graded-guardring diodes were very encouraging. Avalanche gains of over 300 were typical. Several of the diodes exhibited theoretical noise characteristics with gains greater than 600. The series resistance was determined to be approximately 25 ohms from forward bias dc measurements. Capacitance of both types of structures was approximately 1.4 pF at breakdown.

W. N. Shaunfield
Project Engineer

J. R. Biard
Program Manager

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

TECHNICAL REVIEW

A. PURPOSE

Texas Instruments is conducting a program of development aimed at fabricating photodiodes which satisfy the following goals:

1) An NPπP photodetector will be developed which utilizes the avalanche mechanism.
2) The detector will be optimized to operate at 0.9-μm wavelength.
3) Design goals for the detector will be a response of 0.15 ns with a sensitivity equal to or better than that of a photomultiplier tube used at the same wavelength.
4) The photodiodes will operate at and above room temperature and will not be affected by 100° C storage temperature.
5) The photodiodes will be capable of providing amplification of 100 or greater.

The program consists of two phases: I, design and fabrication of the avalanche photodiodes; II, testing and characterization. Phase II will begin with completion of the first diffusion runs to determine whether any modifications in the original design are necessary to achieve the desired characteristics. Specific steps of the program are:

1) Obtain photomasks
2) Determine optimum diffusions
3) Produce experimental epitaxial slices
4) Fabricate experimental planar epitaxial diodes
5) Characterization of experimental diodes, including quantum efficiency, gain characterization, noise performance, and frequency response.

B. GENERAL FACTUAL DATA

Personnel and Hours Worked

Professional	Hours
W. N. Shaunfield	279.0
Jim Lewis	21.0
Total Professional	300.0

Technician	
Jerry Reid	302.9
Pauline Harris	55.0
Jean Athey	55.0
Sam Angelo	41.0
Helen Bryant	16.0
Total Technician	469.9

C. DETAILED FACTUAL DATA

1. Device Design and Fabrication

a. NPπP Structure

In the second quarterly report the problem of edge breakdown in the NPπP structure, and several possible solutions, were discussed. The first of these solutions was to increase further the P-diffusion concentration. It was pointed out that because of the edge effects the P-diffusion concentration would be even more critical than originally expected. One run of the NPπ P structure with an increased P-diffusion concentration was fabricated during the third quarter. For the first time in the NPπP structure with the wide epitaxial layer, breakdown in the active region of the diode was observed. Many areas of the slice still had edge breakdown. Of the diodes which showed breakdown in the active area none had a uniform breakdown; large numbers of microplasmas were present. Either the starting material had imperfections or they were introduced during the diffusion steps.

The technique of etching a moat around the diode, so that the material containing the high electric fields at the edge would be removed, was also investigated. The experiment was unsuccessful, the moat ring on the photomask being too small for accurate exposure of the thick KMER required for etching of silicon. Since a completely planar process is more desirable than a mesa process, it was felt that a new photomask to perform the moat-etching experiment was not justified.

Edge breakdown is the result of peaking of the electric field due to the sharp radius of curvature of the junction. It becomes predominant when the junction depth is small compared to the depletion layer width, as in the wide-epitaxial-layer NPπP structure. This effect could be reduced if the junction were made deeper, resulting in a larger radius of curvature of the junction. Several slices from runs processed earlier were rediffused to make the N-type diffusion deeper, causing the diodes to have active region breakdown.

The rediffused diodes still had edge breakdown, and an examination of their capacitance-voltage characteristics revealed the cause. The NPπP structure is characterized by a high capacitance which decreases rapidly with increasing voltage as the depletion region extends through the high-concentration P-diffusion and then through the low concentration π-layer. A typical capacitance-voltage characteristic is shown in Figure 1 for diode I-1 from run BAPD-3. In the rediffused diode, II-1 from the same run, there is a gradual decrease in capacitance, with increasing voltage indicating that the rediffusion step caused the N-diffusion to move through the P-diffusion region. Bevel lapping and staining of the diodes showed that the N-diffusion moved from approximately 1.0 μm to 1.5 μm during rediffusion. Without the effect of the P-diffusion the diode is an

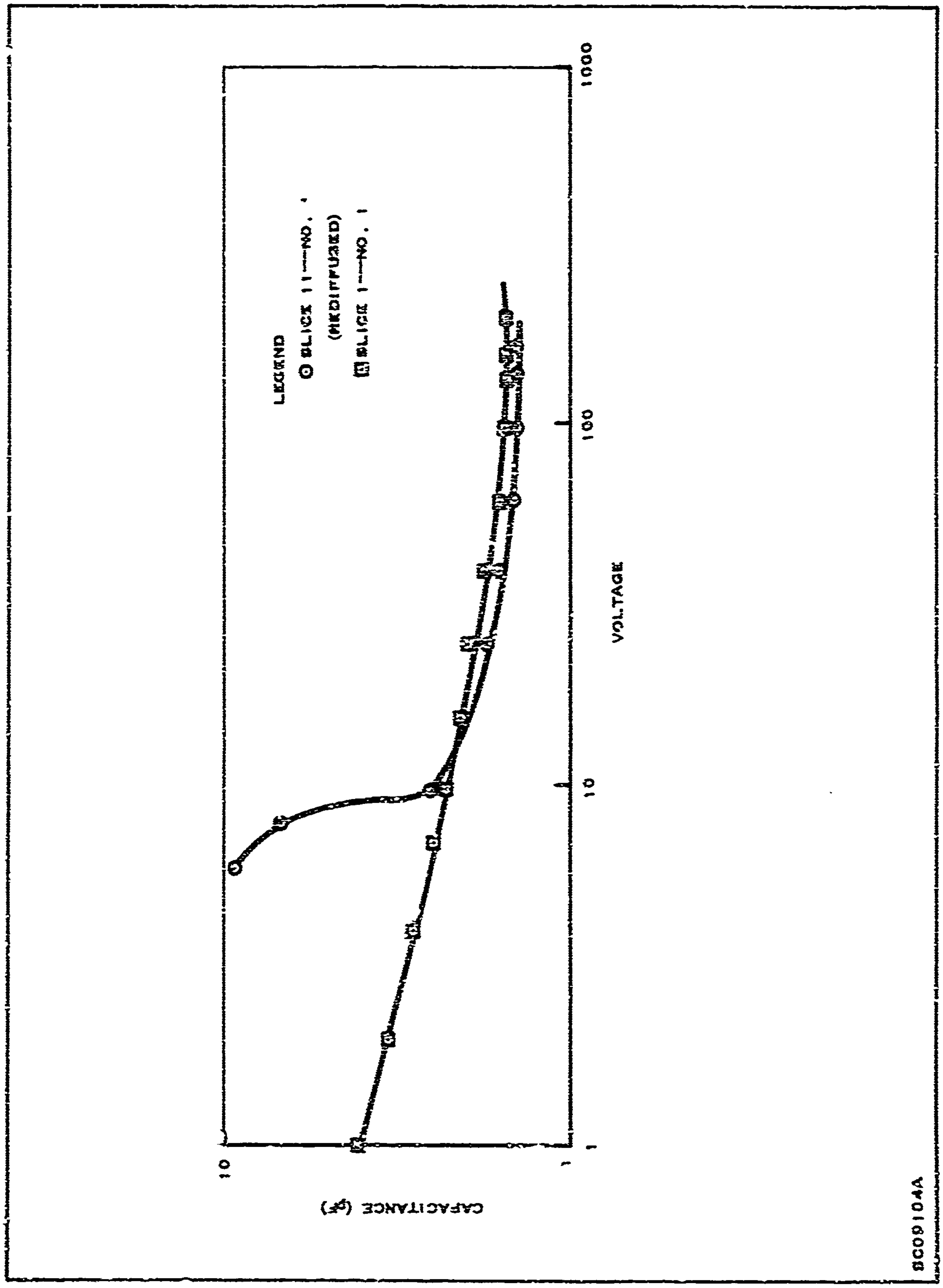


Figure 1. Capacitance versus Voltage for Run BAPD-3

$N\pi P$ diode and would break down on the edge. It was hoped that the P-diffusion would move almost as fast as the N-diffusion, the result being an $NP\pi P$ diode with a larger radius on the N-diffusion.

Because of the problems inherent in the wide-epitaxial-layer $NP\pi P$ structure the effort has been discontinued. No new epitaxial slices were ordered during the third quarter. The remaining time will be spent on the N^+P structure with the graded guardring.

b. <u>N^+P Structure</u>

In the second quarterly report the preliminary results of the first run of the N^+P structure were discussed. The yield was very good and the diodes had high uniform gain. Bevel lapping and staining of the diodes showed the graded guardring junction to be 4–5 μm deep, and the active region to be 1.0 μm deep. During the third quarter an additional run of the N^+P structure was fabricated, with results similar to those of the first run. With these two runs there are sufficient diodes to meet the contract requirements.

Because of the low impurity concentration in the substrate of the N^+P structure, the series resistance is higher than that in the $NP\pi P$ structure. This can be reduced by fabricating the diode in an epitaxial layer on a high-concentration substrate. During the third quarter one run of the N^+P structure was fabricated on epitaxial slices normally used for the $NP\pi P$ structure. Since the epitaxial-layer impurity concentration was too low, the guardring diffusion went too deep and the depletion region punched through the epitaxial layer. As a result the electric field was higher at the edge, and the diodes had edge breakdown. The epitaxial-layer thickness should be so chosen that the combined depth of the diffusion and the width of the depletion region at breakdown are greater than the epitaxial-layer width. New epitaxial material satisfying these requirements has been ordered and the epitaxial N^+P structure, an N^+PP^+ structure, will be fabricated. These new fabrication and material changes are being funded by the company; however, if the effort is successful before the contract is over, this type of diode will be supplied on the contract.

c. Package and Diode Mount

The diodes supplied on the contract are being fabricated in the coaxial pill package shown in Figure 2. Not shown is the lid, which has a lens formed in a 40-mil aperture. Using a collimated light source, such as a laser, the lens projects a spot on the diode less than 10 mils in diameter. The package can be mounted in a PC board or in a BNC connector using the diode mount shown in Figure 3. With the diode and pin installed, the shell is slid inside the BNC connector, making sure the shell contacts the top ring of the diode. In the normal reverse biased mode for the N^+P structure the pin is biased negative with respect to the shell.

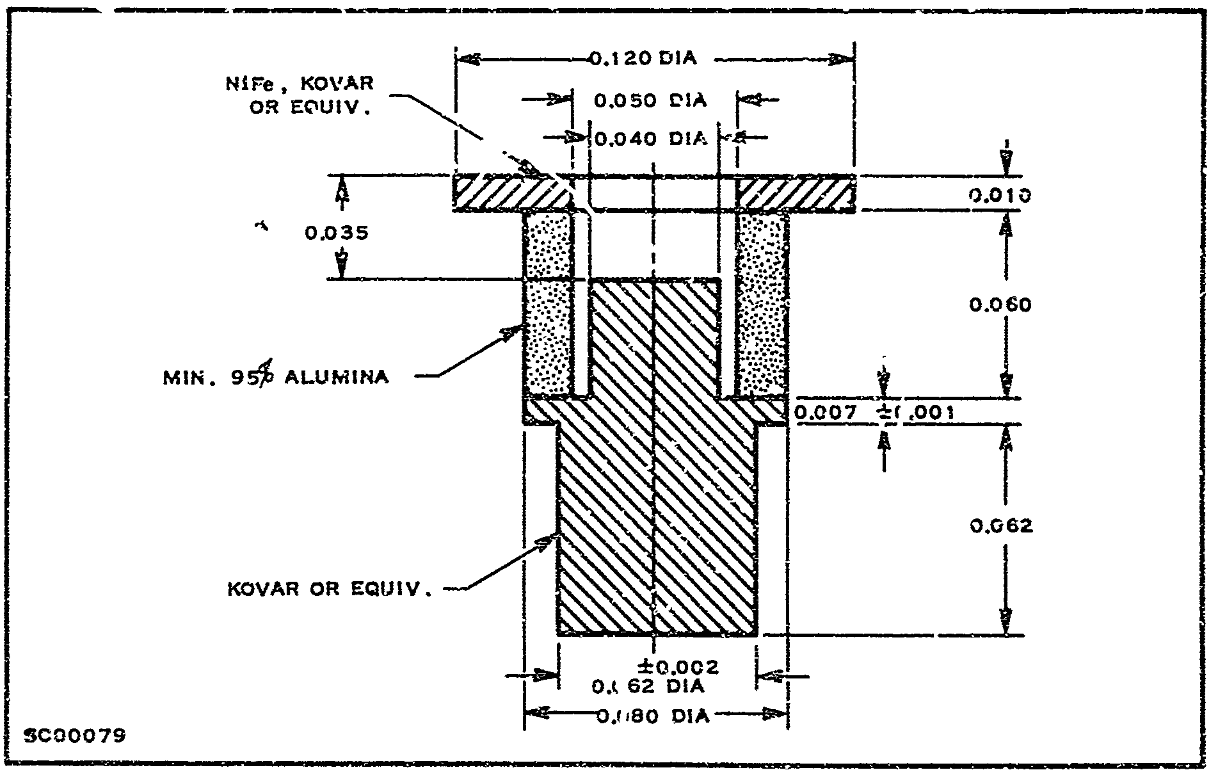


Figure 2. Coaxial Pill Package

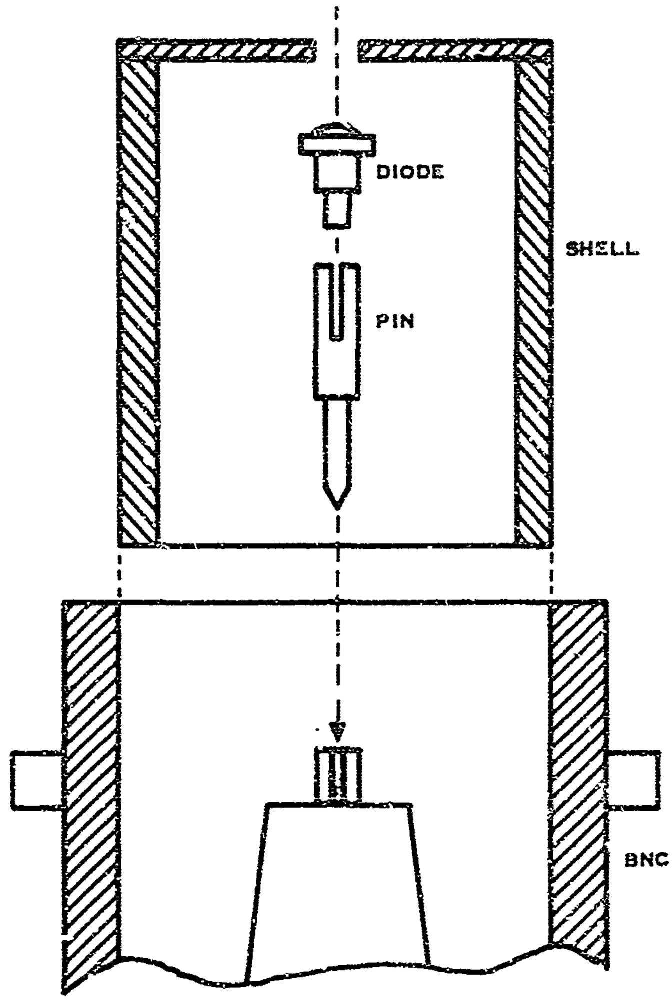


Figure 3. BNC Diode Mount

2. Device Characterization

The following paragraphs describe results obtained from the characterization of 20 state-of-the-art avalanche photodiodes delivered during the third quarter. This group consisted of 10 diodes of the NPπ P structure, runs Nos. BAPD-3 and BAPD-7; and 10 diodes of the N^+P graded-guardring structure, run No. BSAPD-1. A summary of the results obtained is presented in the accompanying table. The 10 NPπ P diodes, although having low gain, represent state-of-the-art devices of the wide epitaxial NPπP

Table: Characteristics of BuShip Avalanche Photodiodes

Run No.	Device No.	Breakdown Voltage Volts	Gain M	Noise Slope d	Bulk Leakage Current nA	Remarks
BSAPD-I	1	167.71	> 400	2.25	—	
	2	171.93	> 300	2.4	—	
	3	167.23	~ 20	—	—	Low gain
	4	173.66	> 640	2.24	0.85	
	5	159.98	~ 200	2.27	—	
	6	170.02	> 350	2.24	0.5	
	7	164.28	~ 280	2.24	1.2	
	8	156.13	~ 80	2.22	1.2	
	9	175.49	> 350	2.23	0.5	
	10	176.59	> 710	2.25	1.5	
BAPD-3I	2	181.35	—	—		Low gain ~2
	3	208.85	—	—		
	4	215.43	—	—		
	6	215.59	2.5	—		
BAPD-3II	1	208.35	4.0	—		Low gain
	3	206.01	2.5	~3		
	5	196.69	4.0	~2.28		
BAPD-7III	1	274.91	2.0	—		Low gain
	2	288.72	—	—		
	3	268.35	—	—		

structure, and were included since that was the original structure proposed. The $N^{+}P$ diodes are much superior in performance and, because of their high gain, allowed a more complete characterization.

a. Capacitance

The capacitance of both types of diodes is approximately 1.4 pF at breakdown. A typical capacitance-voltage characteristic is shown in Figure 1 for the

$NP\pi P$ structure and Figure 4 for the N^+P structure. The capacitance measurements were made on diodes mounted in the coaxial pill package which has a package capacitance of 0.3 pF. Since the measurements were made at low frequency, 1 MHz, the junction capacitance can be found by subtracting the package capacitance from the measure capacitance. At high frequencies the diode series resistance would complicate the computation.

b. Gain Characteristics

Avalanche gain for the measurements was found by taking the ratio of the diode photocurrent at high reverse bias near breakdown to the photocurrent at a low bias below breakdown. Although the measurements can be made at dc, the test on the diodes was made using a 400-Hz amplitude modulated light source at 9200 Å. Using the photoresponse at 30 volts for a reference gain of one, the typical gain-voltage characteristic for a graded-guardring diode is shown in Figure 5. The gain-voltage characteristic for avalanche has been described by Miller* as

$$M = \frac{1}{1 - (V/V_B)^n}$$

For the data shown in Figure 5 and $M > 16$, n in the above equation is 0.42. For lower gains n becomes larger.

The gain shown in the table is the gain at which the measuring circuit saturated or excess noise occurred, indicating a microplasma went into sustained breakdown.

---

* S. L. Miller, "Ionization Rates for Holes and Electrons in Silicon," Phys. Rev., Vol. 105 (February 1957), pp. 1246-1249.

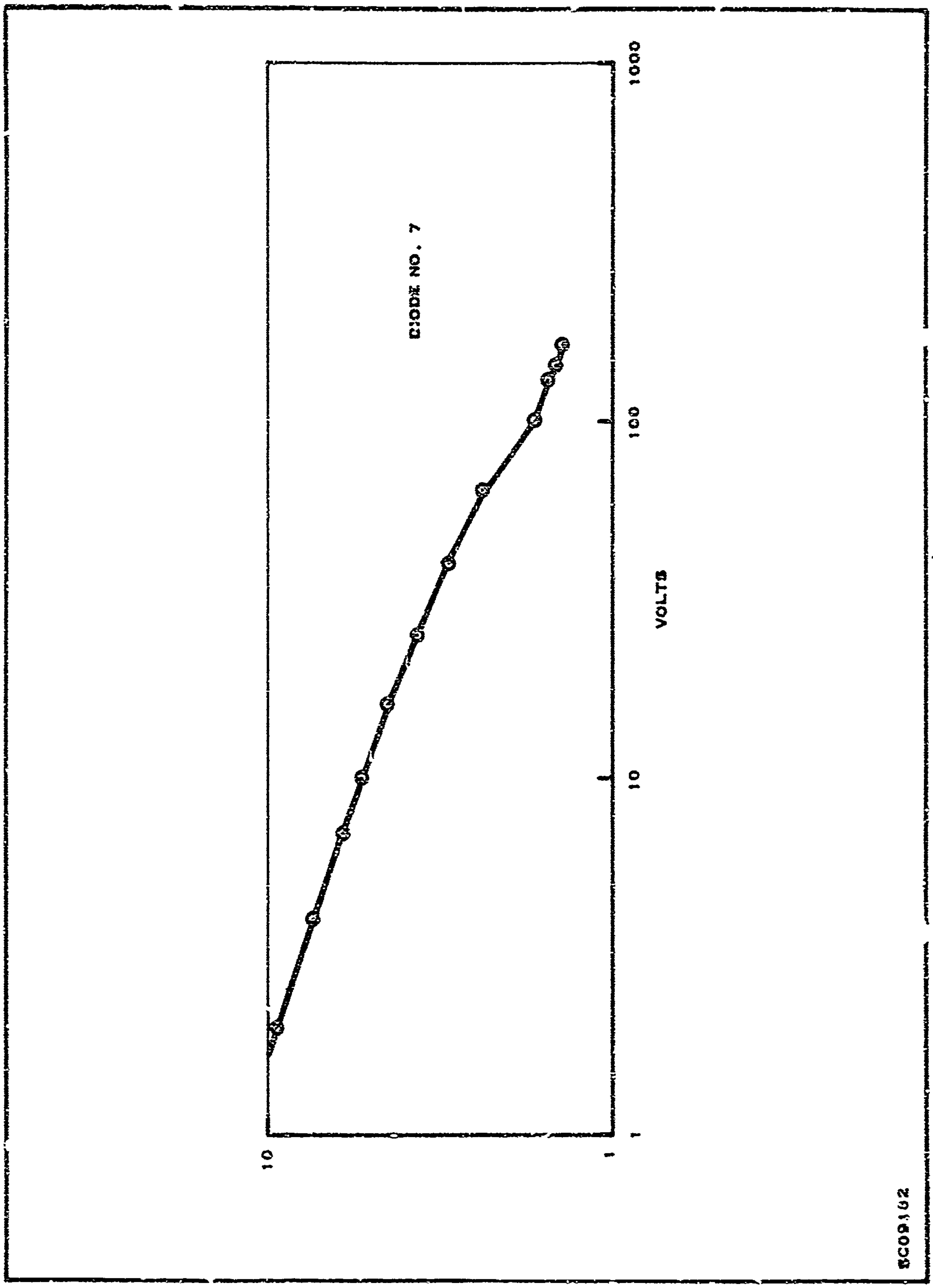


Figure 4. Capacitance versus Voltage for $N^+ P$ Structure (Run BSAPD-I)

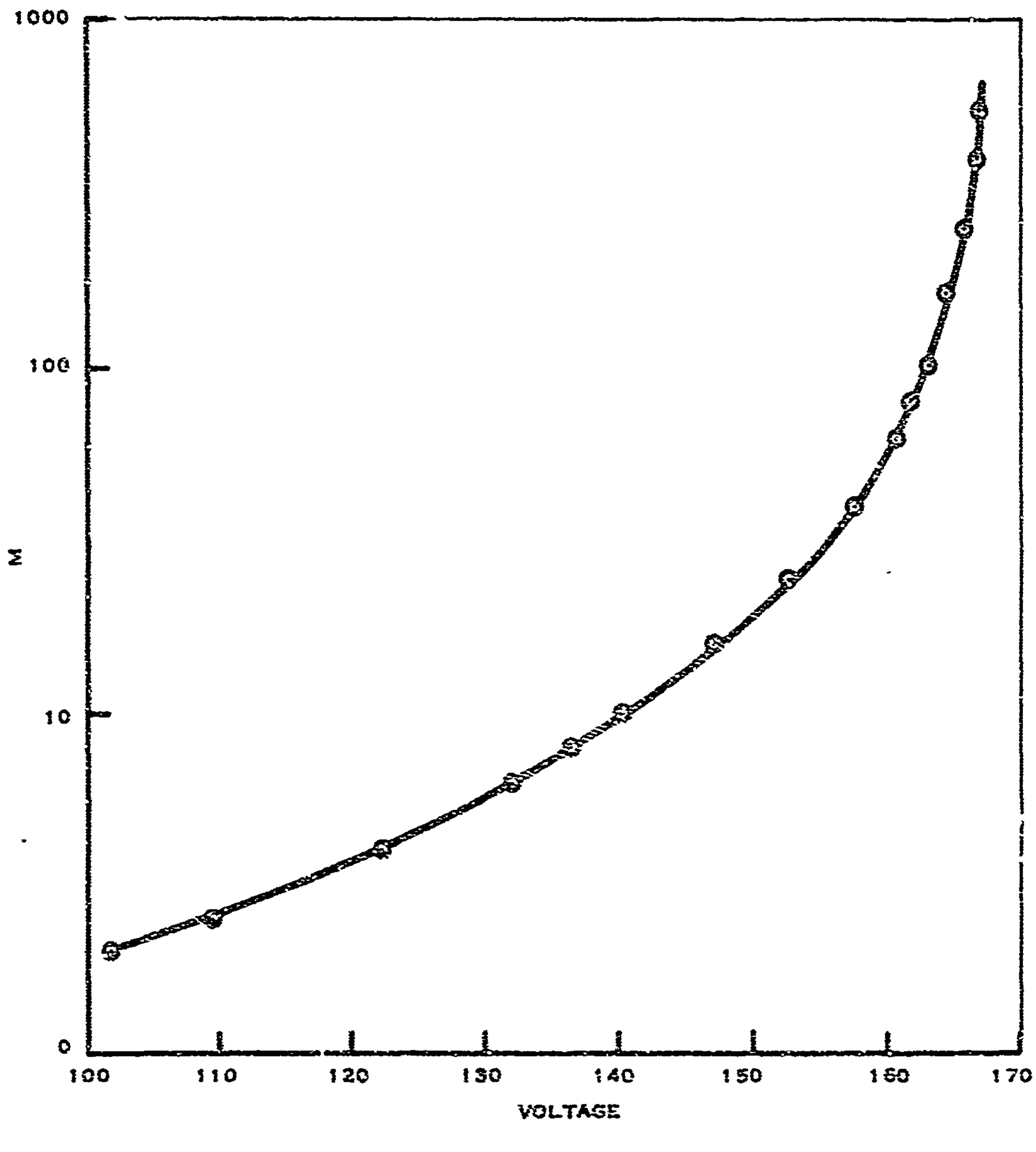


Figure 5. Avalanche Gain versus Bias Voltage for Diode BSAPD-I No. 1 at 9200 Å

c. Noise Characteristics

The noise of the avalanche process has been described by McIntyre* as

$$\overline{i_n^2} = 2\,q\,\Delta f\,I_\Phi\,M^d$$

where

Δf is the bandwidth

I_Φ is the dc photocurrent

q is the electronic charge

M is the gain

d is the noise slope

The noise current squared was measured in a system at a center frequency of 3.8 KHz and a bandwidth of 2.3 KHz. A plot of the typical characteristics is shown in Figure 6. The dc photocurrent was 16.5 nA. The data are in agreement with the above equation over 7 decades of noise. The noise power is found to increase with M to the 2.25 power. The measuring circuit saturated at M = 710, and measurements were not taken at higher gains. The value for d for the other diodes is shown in the table. Diodes BSAPD-I Nos. 3 and 8 showed a sharp rise in noise from the theoretical, indicating that microplasmas were present in the active area.

d. Bulk Leakage Current

Because of the high substrate resistivity (6.5 Ω cm) of the graded-guardring structure, this structure has a higher bulk leakage current than the NPπP

* R. J. McIntyre, "Multiplication Noise in Uniform Avalanche Diodes," IEEE Trans. on Electron Devices, Vol. ED-13, No. 1 (January 1966), pp. 164-168.

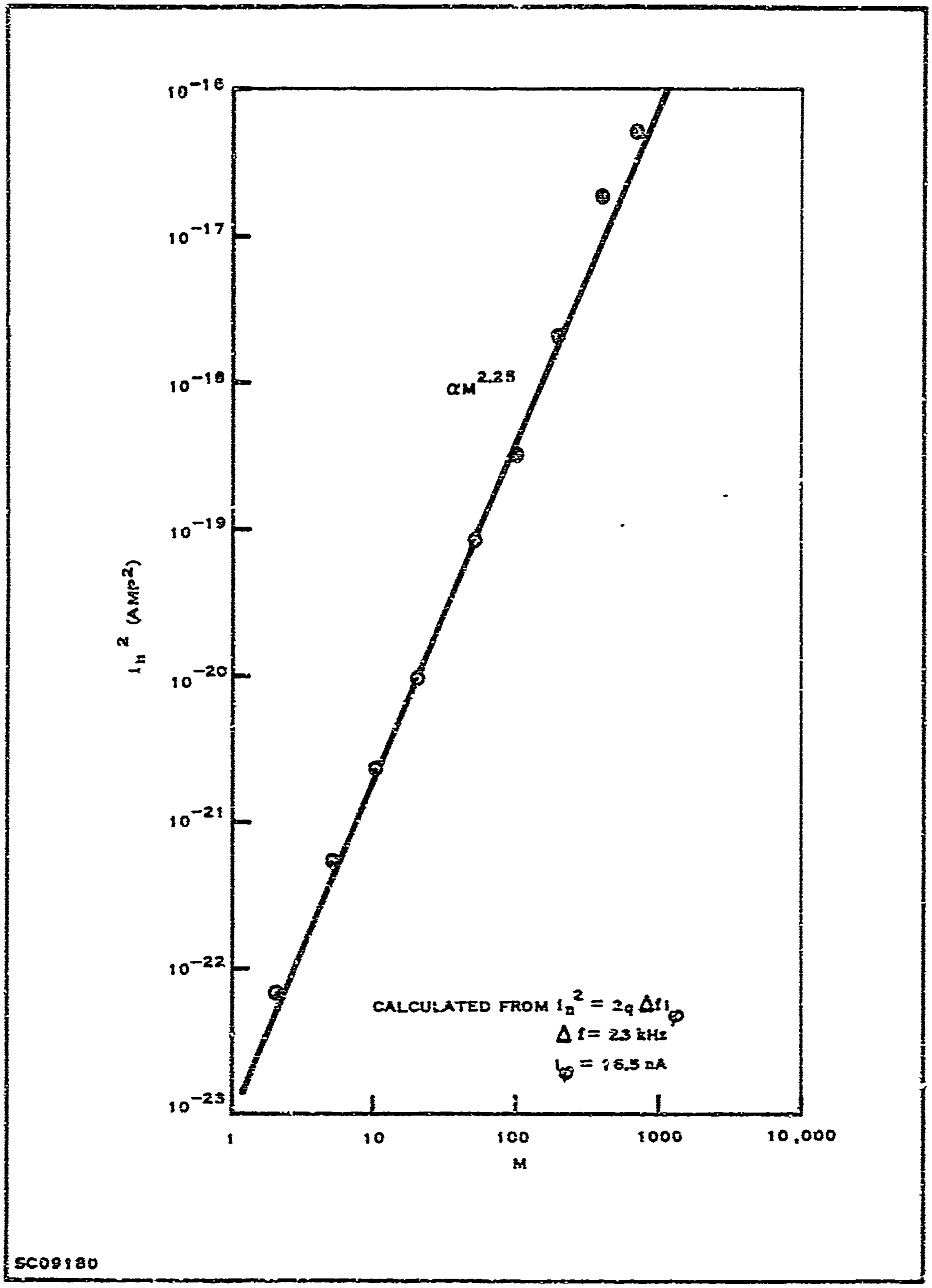


Figure 6. Noise Current Squared versus M(BSAPD-I No. 10)

structure. It is high enough to be measured by plotting the total leakage current versus avalanche gain. Since the surface leakage current is not multiplied, the slope of the curve is the bulk leakage current. The measured bulk leakage, recorded in the table, is typically from 0.5 to 1.5 nA.

e. High-Frequency-Gain Characteristics

The avalanche gain was measured at 540 and 1080 MHz and compared with the dc gain. The signal source was an HeNe laser operating at 6328 Å with beat notes at the above frequencies. Reverse bias was supplied through a dc bias tee; the signal was fed directly to a Tektronix Type 661 sampling scope and an HP Type 3406A sampling voltmeter. The dc gain was measured by taking the ratio of the dc photocurrent at the bias voltage and 30 volts. Multiplied photocurrent, $M_{dc}I_{\Phi}$, was held constant at 1.0 mA to allow the signal to be seen at low gain while avoiding current saturation effects present at high gains. To avoid the high capacitance effects present at low-bias voltages, the $M_{ac} = 10$ as a reference the ac gain at higher gains was determined. A typical curve of ac gain us dc gain is shown in Figure 7. The above assumption is shown to be valid since the ac and dc gain is equal out to a gain of 40. Saturation of the ac gain indicates that the diodes have a gain-bandwidth product of approximately 80 GHz.

f. Equivalent Circuit

The avalanche photodiode can be represented by the equivalent circuit shown in Figure 8. The signal current, i_s, is mMI_{Φ} sin wt where m is the modulation index. The noise, represented by $\overline{i_n^2}$, was given earlier. Junction capacitance, C_j, is equal to the measured capacitance minus the package capacitance C_p, 0.3 pF for the pill package. The series resistance, R_s, is typically one ohm for the NPπP structure. The series resistance for the BSAPD-1 run was determined to be approximately 25 ohms from forward bias dc measurements.

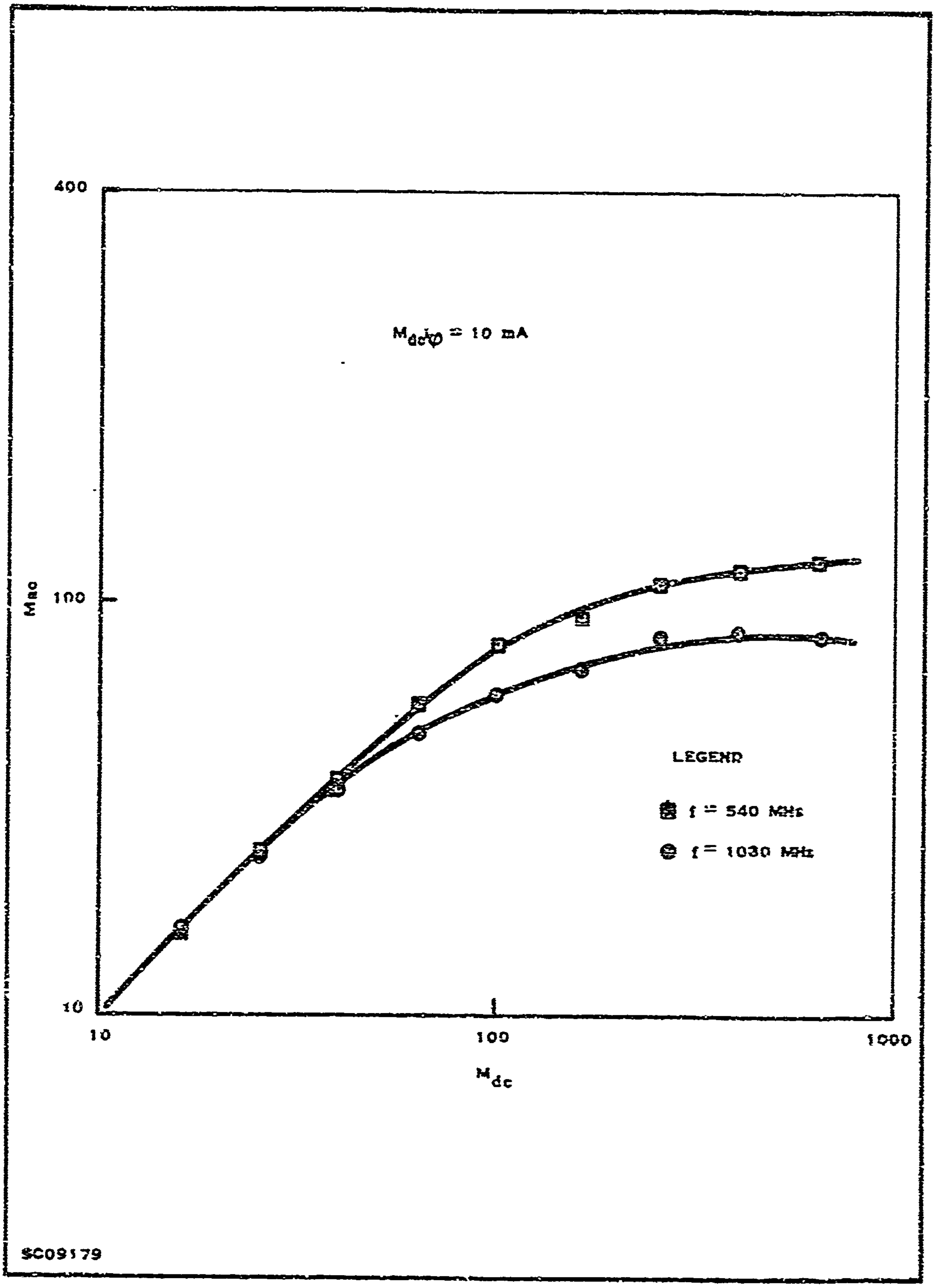


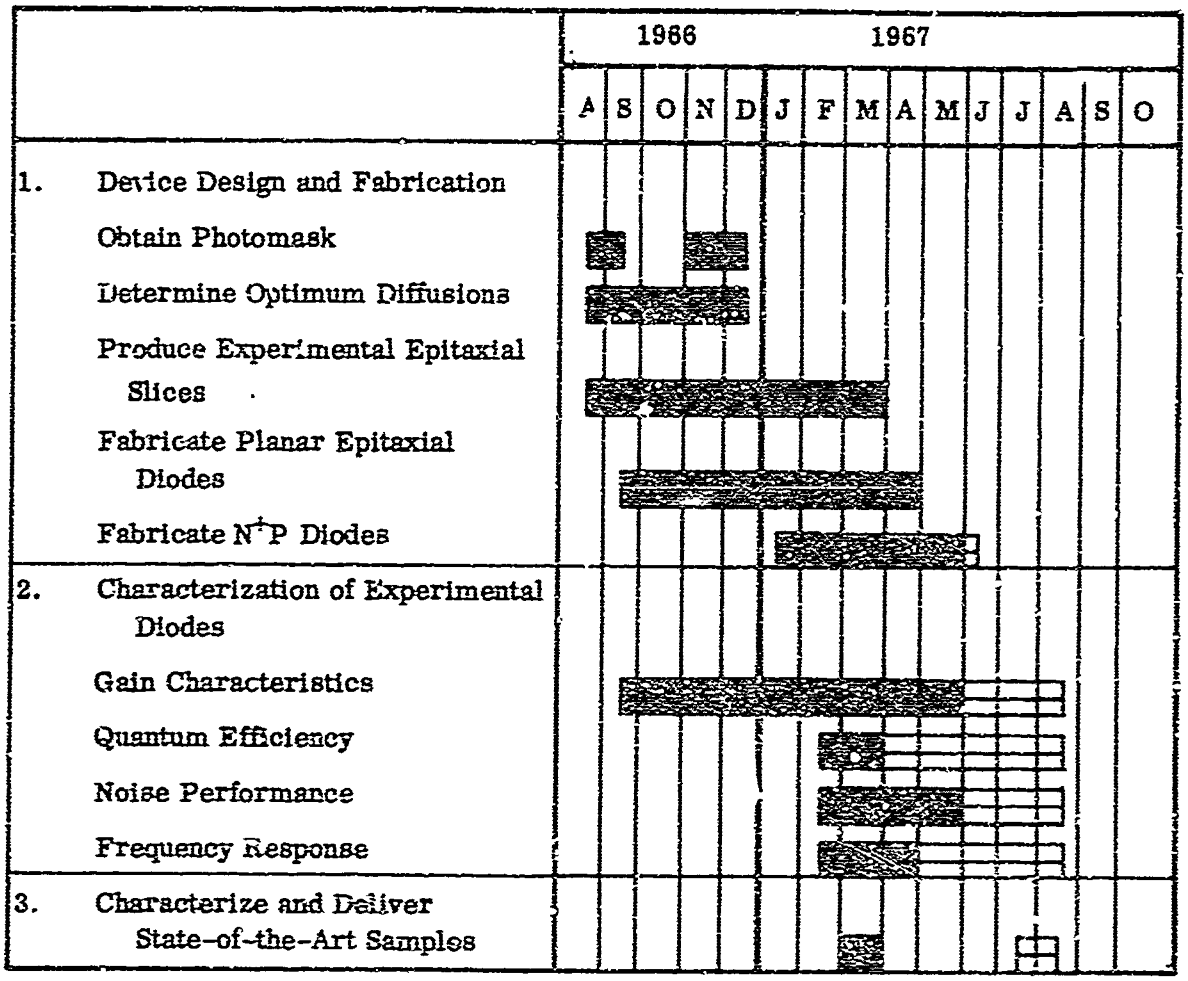
Figure 7. M_{ac} versus M_{dc} (BSAPD-I No. 1)

3. Project Performance and Schedule

Texas Instruments Incorporated

Contract No. NObsr 95337 (Report) Date: July 1967

Period Covered: 16 February to 16 May 1967



SC07948A

Legend:

Work Performed

Schedule of Projected Operation

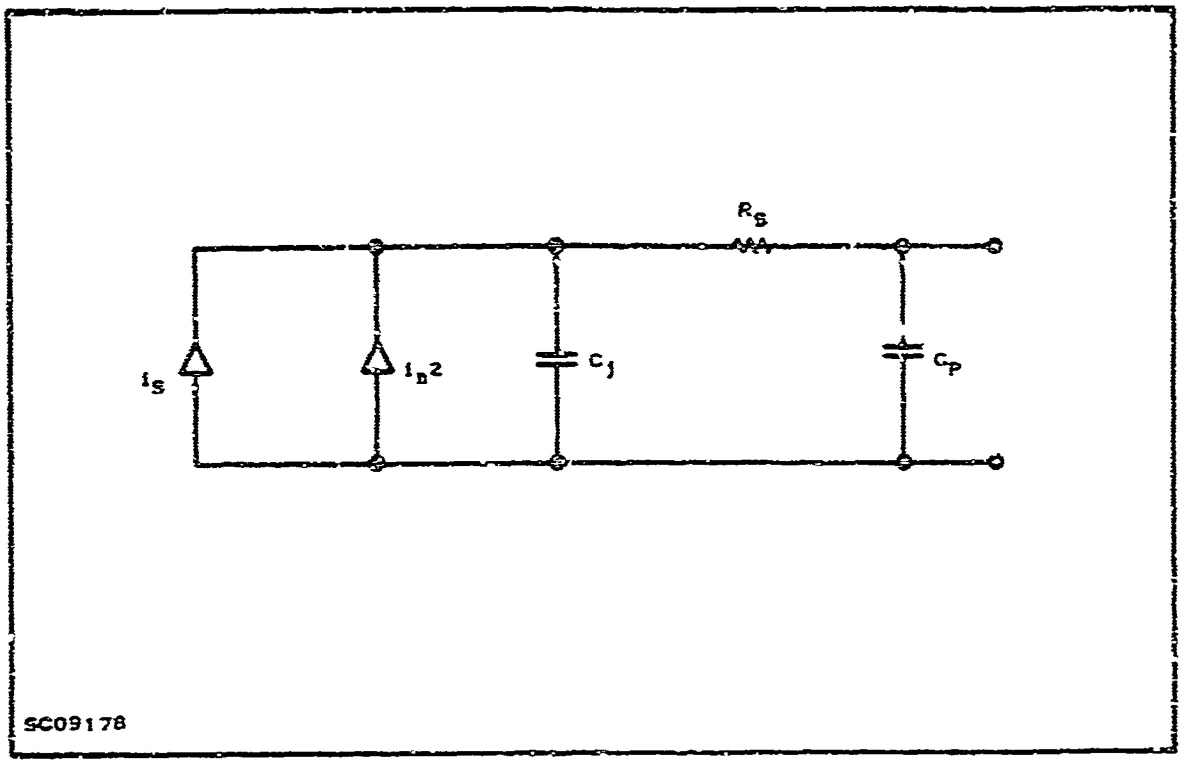


Figure 8. Avalanche Photodiode Equivalent Circuit

Item: Estimated completion in percent of total effort expected to be expended (not chronological).

1)	Obtain Photomasks	100%
2)	Determine Optimum Diffusions	100%
3)	Produce Experimental Epitaxial Slices	100%
4)	Fabricate Planar Epitaxial Diodes	100%
5)	Fabricate N^+P Diodes	75%
6)	Determine Gain Characteristics	75%
7)	Determine Quantum Efficiency	20%
8)	Determine Noise Characteristics	60%
9)	Determine Frequency Response	20%
10)	Characterize and Deliver Samples	50%

D. CONCLUSIONS

A run of NPπP diodes was fabricated with avalanche breakdown in the active region. However, there were microplasmas and the gains were low.

An additional run of N^+P diodes was fabricated, and there was a large number of good diodes.

Characterization of the 20 state-of-the-art samples was completed. Several N^+P diodes exhibited theoretical noise characteristics up to gains of 600. Based on results of the two types of structures, the NPπ P structure effort is being discontinued in favor of the N^+P structure.

SECTION II

PROGRAM FOR NEXT INTERVAL

For the next quarter we plan the following work:

1) Mount diodes from runs BSAPD-I and II for final characterization.
2) Run complete characterization on final state-of-the-art samples.
3) Fabricate and characterize N^+PP^+ diodes if time permits.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Texas Instruments Incorporated Dallas, Texas 75222	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Development and Fabrication of Solid-State High-Speed Optical Detectors

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Third Interim Engineering Report 16 February 1967 to 15 May 1967

5. AUTHOR(S) (Last name, first name, initial)

Shaumfield, Wallace N.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1967	19	2

8a. CONTRACT OR GRANT NO. NObsr 95337 b. PROJECT NO. SF021-02-01 c. Task No. 9349 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 03-67-53 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Navy Department, Bureau of Ships, Electronics Division

13. ABSTRACT

Work continued on development and fabrication of a high-speed silicon avalanche photodetector optimized for operation at 0.9 μm. During this quarter work was concentrated on the fabrication and characterization of diodes. A run of NPπP diodes was completed with avalanche breakdown taking place in the active region instead of the edge. However, there were microplasmas, and the gains were low. A new run of the graded-guardring structure was completed, and the yield was high. With this run and the run processed earlier there are sufficient diodes to meet the contract requirements. Twenty state-of-the-art samples were characterized and delivered. Results on the N^+P graded-guardring diodes were very encouraging. Avalanche gains of over 300 were typical. Several of the diodes exhibited theoretical noise characteristics with gains greater than 600. The series resistance was determined to be approximately 25 ohms from forward bias dc measurements. Capacitance of both types of structures was approximately 1.4 pF at breakdown.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
High-speed photodetector						
Avalanche photodiode						
Silicon photodetector						
Low-noise photodiode						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_______________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_______________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_______________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Unclassified
Security Classification